A Field Study of Footprint-Scale Variability of Raindrop Size

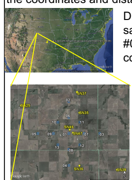
Leo Pio D'Adderio (Depaertment of Physics and Earth Science, University of Ferrara, Italy), Ali Tokay (JCET-University of Maryland Baltimore County and NASA-Goddard Space Flight Center, Greenbelt, MD, USA), Federico Porcù (Department of Physics and Astronomy, University of Bologna, Italy), Walter A. Petersen and David B. Wolff (NASA Wallops Flight Facility, Wallops Island, VA, USA)

1. Introduction

The retrieval of raindrop size distribution (DSD) from dual frequency precipitation radar (DPR) on board GPM core satellite is one of the key objectives of the NASA's Global Precipitation Measurement (GPM) mission. The footprint of the DPR is nearly circular at approximately 5 km diameter and the non-uniform beam filling (NUBF) within the footprint is one of the uncertainties of the retrieved size distribution. The NUBF occurs in both horizontal and vertical dimension and results from the combination of the gradient of rain intensity and partial filling within the footprint. The embedded convection and the squall lines with trailing stratiform rain are frequently observed during frontal passage and result in sharp gradients in rain intensity within a few kilometers. The air mass thunderstorms and patchy stratiform rain in the presence of dry layer near the Earth's surface results in gaps in the DPR footprint. This study investigates the horizontal spatial variability of DSD due to the gradient of rain intensity within DPR footprint through disdrometer measurements collected during Mid-latitude Continental Convective Clouds Experiment (MC3E).

2. Sites and Instrumentation

The MC3E campaign was a joint effort involving the United States Department of Energy's Atmospheric Radiation Measurement (ARM) and the NASA GPM ground validation (GPMGV) programs. The campaign was conducted in North Central Oklahoma (36.7N, 97.1W) from April 22 through June 6, 2011. Seven (five GPMGV and two ARM) third-generation compact two-dimensional video disdrometers (2DVD) were deployed at and around the ARM Southern Great Plains site where the distances between the units ranged from 0.4 to 9.2 km. Given the fact that the 2DVDs require power and open space, the logistics dominate the site selection. While the configuration of the 2DVDs was not ideal, the layout and number of units allowed interpolating the 2DVD measurements to desired sites. Figure 1 shows the locations and interpolation points of the 2DVDs. Table 1b presents the coordinates and distances between the 13 interpolated sites.



Due to symmetry, the distances between the interpolated sites can be the same. For instance, site #01 is 2.5 km distance to sites #02, #03, #04, and #05. This configuration allowed studying the directional changes in the correlations based on storm orientation.

Site #	01	02	03	04	05	06	07	08	09	10	11	12	13
	36.60° 97.49°	36.63° 97.49°	36.60° 97.48°	36.58° 97.49°	36.60° 97.52°	36.62° 97.89°	36.60° 97.47°	36.59° 97.49°	36.60° 97.47°	36.61° 97.50°	36.61° 97.48°	36.60° 97.48°	36.60° 97.50°
01		2.50	2.50	2.50	2.50	1.26	1.25	1.25	1.25	1.25	1.25	1.25	1.25
02			3.54	5.00	3.54	1.24	2.80	3.75	2.80	1.84	1.84	3.50	3.50
03				3.54	5.00	2.80	1.25	2.79	3.75	3.50	1.84	1.84	3.50
04					3.54	3.76	2.80	3.75	2.80	3.50	3.50	1.84	1.84
05						2.80	3.75	2.79	1.25	1.84	3.50	3.50	1.84
06							1.77	2.51	1.77	0.96	0.96	2.32	2.32
07								1.77	2.50	2.31	0.96	0.96	2.31
08									1.77	2.31	2.31	0.96	0.96
09										0.96	2.31	2.31	0.96
10											1.77	2.50	1.66
11												1.77	2.50
12													1.77
13													

3. Data Analysis and Methodology

Four different rain/no-rain thresholds are then applied to the one-minute observations. All thresholds use minimum of 10 drops. The minimum RR of 0.1 mm h^{-1} was applied to the 13 interpolated sites and the rainfall below this threshold was set to zero. The same RR threshold was also applied to the areal average rainfall resulting a sample size of 723. Applying the minimum detectable reflectivity of the normal (Ku-band) and the high-sensitive (Ka-band) scans of 13 dB and matched (Ka- and Ku-bands) scan of 18 dB to the areal average reflectivity, the sample sizes were 698, 703, and 639, respectively. A three-parameter exponential function was used to investigate the spatial variability of fifteen DSD parameters. The exponential function is expressed as:

$$r = r_0 \exp\left[-\left(\frac{d}{d_0}\right)^{s_0}\right]$$

where r_0, s_0 are nugget and shape parameters, respectively, and d_0 is the correlation distance. The Pearson correlation coefficient, r, is calculated between the paired 2DVD observations at distance, d. The r_0 is the nugget-correlation between the collocated observations and is set to 0.99 in the absence of collocated 2DVDs. Following Tokay et al. (2016) methodology, an initial guess was made for d_0 and s_0 using ranges of 0 to 300 at an increment of 0.1, and 0 to 2 at an increment of 0.01, respectively. The d_0 and s_0 are calculated minimizing the root-mean square error (RMSE) between the observation and equation based correlations. The RMSE is the measure of the goodness of the fit and it is critical for the interpretation of d_0 and s_0.

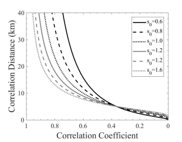


Figure shows the sensitivity of d_0 to r for six different s_0 when d and r_0 are set to 5 km and 0.99, respectively. At d = 5 km, r is equal to r_0 * (1/exp), 0.364. When r is less than 0.364, d_0 increases with s_0 and vice versa is true when r is greater than 0.364. Considering r of 0.6 at 2 km distance, d_0 would be 4 and 8 km if s_0 were 1.0 and 0.5, respectively. Thus, s_0 plays an important role in determining d_0 for a given correlation at particular distance.

4. Raindrop Size Distribution

Following GPM DPR algorithm, three-parameter normalized gamma distribution is adopted to determine the spatial variability of DSD parameters. The normalized size distribution is expressed as:

$$N(D) = N_W f(\mu)\left(\frac{D}{D_{mass}}\right)^{\mu} \exp\left[-(4+\mu)\frac{D}{D_{mass}}\right]$$

where f(μ) is given as a function of the shape parameter, μ

$$f(\mu) = \frac{6}{4^4}\frac{(4+\mu)^{\mu}}{\Gamma(\mu+4)}$$

The D_{mass} and N_W are the other two parameters of normalized gamma distribution. D_{mass} is the ratio of fourth to third moment of size distribution, while N_W is related to liquid water content, W, and D_{mass} and is given as:

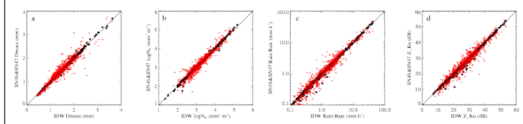
$$N_W = \frac{4^4}{\pi\rho_w}\frac{10^3 W}{D_{mass}^4}$$

where ρ_w is the density of water. Since D_{mass} and W are calculated from the observed size distribution, N_W is a direct output of the 2DVD observations. N_W values span nearly five orders of magnitude, therefore, logarithmic values are used to determine its spatial variability.

The shape parameter has a wide range where the bounds are subjectively predetermined following method of moments. It is sensitive to the choice of moments and whether or not the truncated moments are used. In this study, the shape parameter was determined by minimizing the rain rate difference between the observed size distribution and that computed from a normalized gamma distribution. An initial guess between -2 and 23 with 0.1 increments was the input for the shape parameter when the rain rate is calculated from gamma distribution.

5. Inverse Distance Weight (IDW)

Precipitation products based on point measurements rely on interpolation of the measurements in selected grid spacing. The performance and reliability of interpolation algorithms depends highly on climate, season and terrain, as well as instruments' spatial distribution, sampling interval and density. The IDW technique is considered as baseline algorithm for benchmarking more advanced interpolation techniques that require detailed knowledge of precipitation spatial properties. All available instruments (e.g. 2DVDs) are used to perform the interpolation. A physical parameter (e.g. rain rate) at a desire site is obtained through a weighted average of the same parameter measured by surrounding instruments. The weights are defined as d^{-b}, where d is the distance between the desired site and each of the surrounding instruments. The exponent b has to be determined by considering the measurement accumulation time and precipitation characteristics. A simple and robust choice is to set b=2, considering that the results of interpolation vary slowly with b, and this value was used in this study where IDW was applied to one-minute, bin-by-bin size spectrum for the first time.

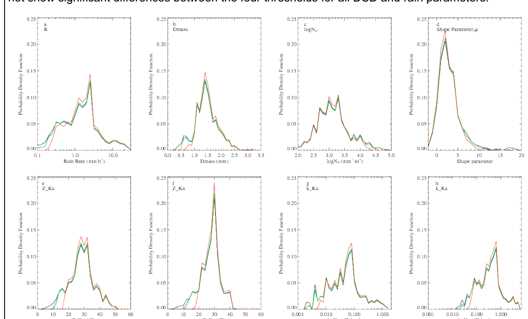


The accuracy of the IDW was tested through cross comparison of four physical parameters, D_{mass}, $\log N_W$, R, and Z_Ku, between SN46 and site # 1 and between SN47 and site #1. Site #1 is 0.15 and 0.34 km from SN46 and SN47, respectively. There were 707 samples where SN46 and SN47 measured R ≥ 0.1 mm h^{-1}. Figure reveals that there is excellent agreement between the observed and interpolated parameters. There was also no systematic over- or under-estimation of any parameter. Site #1 had a better agreement with SN46 due to its closer distance. The statistics presented in Table 3 confirm the excellent agreement. Bias is the difference of the physical parameter between its interpolated and measured value. We present the percent bias where bias is divided by mean value of the observed parameter. Since the measurement site is considered as a reference, bias and absolute bias are also considered as mean error and mean absolute error. Rain rate was slightly overestimated with 0.6% and 1.8% bias and 4% and 20% absolute bias with respect to SN46 and SN47, respectively.

Parameter	bias (%) SN46	abs. bias (%) SN46	bias (%) SN47	abs. bias (%) SN47
D_{mass}	0.8	1.8	-0.4	7.3
$\log N_W$	-0.3	0.9	0.4	3.7
R	0.6	4.0	1.8	20.0
Z_Ku	1.0	1.8	0.9	6.9

6. Probability and Cumulative Distribution Functions (PDF & CDF)

PDF of three parameters of normalized gamma distribution, five parameters of bulk descriptors of rainfall are presented for four different rain/no-rain thresholds. All eight physical parameters are calculated through averaging their values at 13 interpolation sites. The sample size decreased noticeably from R based threshold to Z based thresholds, reaching its minimum at Z_Ka&Z_Ku based threshold where light rain was eliminated considerably. This can be identified visually at the left tail of the PDF of D_{mass} and rain parameters. The PDF of $\log N_W$ and m, on the other hand, had lower percentages at the upper tail for reflectivity-based thresholds. The breadth of the PDF does not show significant differences between the four thresholds for all DSD and rain parameters.



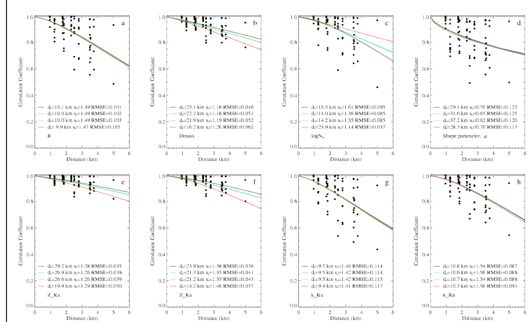
There were significant differences between areal mean and individual site maximum values. The maximum value of D_{mass} was 3.27 mm for an area mean but is 3.63 mm at the site. For R, the areal mean was 28.8 mm h^{-1}, while one of the sites reported 70.1 mm h^{-1}. It should be reminded that these maximum values are relatively high globally due to the nature of rain during MC3E. The spring and summertime continental rain often includes heavy bursts in Oklahoma. The Z_Ku of 56.3 dBZ at a site was another indicator of heavy burst. The maximum Z_Ku at areal mean was 5.6 dBZ lower than that at a site.

Moderate-to-heavy rain in the southern Great Plains receives a relatively high percent of contribution from large drops (> 3 mm in diameter). Indeed, the world largest drop ever observed by a disdrometer, 9.7 mm in diameter, occurred during MC3E. It is assumed that melted graupel near the surface created this giant raindrop. The presence of large drops resulted in 14% of the observations D_{mass} ≥ 2.0 mm at Z_Ka&Z_Ku threshold. For the same threshold, 11% and 16% of the observations had Z_Ku ≥ 40 dBZ and k_Ka ≥ 1 dB km^{-1}, respectively. The MC3E dataset exhibited drastically different properties than the preceding study conducted at the mid-Atlantic coastal site of Wallops Island, Virginia where virtually no observations of R ≥ 10 mm h^{-1}, D_{mass} ≥ 2.0 mm, and Z_Ku ≥ 40 dBZ occurred.

The shape parameter was set to 2 in the GPM Combined and 3 in the GPM DPR algorithms. Interestingly, the PDF of shape parameter exhibited a sharp peak where 80% of the observations fell between 0 and 5 with the peak between 2 and 3 at Z_Ka&Z_Ku threshold. It should be noted that a gamma distribution is not always the best choice for modeling observed size distribution. For example, a drop break-up induced size distribution typically exhibits a bimodal distribution with the result being gamma fits that result in artificially high shape parameters.

7. Spatial Variability: Correlations

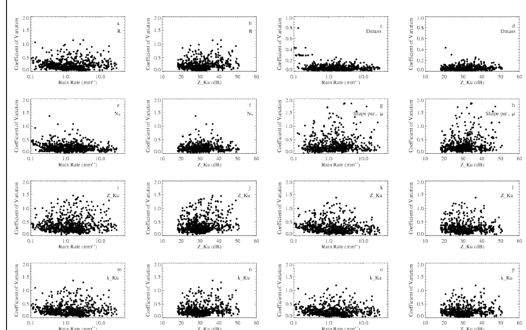
Correlations coefficients for eight parameters were calculated between 13 interpolated sites for four different rain/no-rain thresholds. Figure shows the 78 paired correlations for the R threshold only but fitted curves and corresponding parameters of the exponential function are given for all four thresholds. Due to the symmetry of the selected interpolated sites, there were multiple correlations at a given distance. The center point, site #01, for instance, was 1.25 km distance from eight different sites. The correlations differed substantially at the same distance as a result of storm orientation even though the database is a combination of multiple events.



Considering correlations between site #01 and surrounding sites, the variability of R was greatest in the northeast where correlations fell below 0.84 at 1.25 km distance. The correlations were also below 0.90 to the north but remained around 0.94-0.97 for the other directions at the same distance. At 2.5 km distance, the correlations were below 0.60 and 0.70 at south and north direction, respectively, but were above 0.86 and 0.91 at west and east directions, respectively. This demonstrates a nature of rainfall variability. The degree of rainfall uniformity is highly different from one event to another as well as within a given event.

8. Spatial Variability: Coefficient of Variation (CV)

The CV is the ratio of standard deviation to the mean value and is preferable to standard deviation since it is a normalized quantity. The mean value and its standard deviation of eight physical parameters were calculated among 13 sites for each sample in linear space. The CV of the physical parameters was then presented as a function of areal average rain rate for R threshold and as a function of Z_Ku for Z_Ku&Z_Ka threshold.



All physical parameters had CV ≤ 1.25 except the shape parameter of the modeled gamma distribution. The vast majority of R had CV ≤ 0.5, only 8% of the observations showed moderate to extreme variability (CV > 0.5). There were two samples where CV of R exceeded 1.0. These samples corresponded to Z_Ku of 41.2 and 36.8 dB and R of 3.2 and 1.6 mm h^{-1} and all thirteen sites reported rainfall in both samples.

CV	R	D_{mass}	N_W	Shape par., μ	Z_Ku	Z_Ka	k_Ku	K_Ka
≤0.25	0.664;0.689	0.968;0.995	0.687;0.725	0.532;0.563	0.367;0.390	0.530;0.581	0.550;0.570	0.651;0.685
0.25-0.50	0.256;0.227	0.030;0.005	0.270;0.238	0.261;0.273	0.404;0.372	0.339;0.296	0.331;0.302	0.267;0.228
0.50-0.75	0.058;0.061	0.000;0.000	0.033;0.028	0.090;0.089	0.118;0.117	0.075;0.066	0.066;0.070	0.055;0.058
0.75-1.00	0.018;0.020	0.001;0.000	0.006;0.005	0.030;0.033	0.062;0.064	0.041;0.041	0.040;0.045	0.019;0.022
>1.00	0.004;0.003	0.000;0.000	0.004;0.005	0.087;0.096	0.050;0.056	0.015;0.017	0.012;0.013	0.007;0.006

Acknowledgments

The authors are thankful to Robert Meneghini, Mircea Grecu, and S. Joseph Munchak for their valuable comments from GPM algorithm developer perspective. Thanks to Jianxin Wang for his help on IDL plotting routine. Many thanks to Patrick Gatlin and Matthew Wingo for maintaining and collecting 2DVD data during MC3E. Acknowledgments extend to V.N. Bringi and Merhala Thurai for their efforts in calibrating 2DVD at the beginning of the field campaign. We appreciate DOE ARM for hosting the field campaign in their Southern Great Plains facility and providing two 2DVD database. We acknowledge funding support from the GPM Ground Validation program provided by Matthew Schwaller. This research was funded through NASA Precipitation Measurement Mission grant NNX16AD45G provided by Ramesh Kakar.